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# Flue Gas Desulfurization Pilot Study. Phase I Survey of Major Installations. Appendix 95-B Lime/Sludge Flue Gas Desulfurization Process

NATO Committee on the Challenges of Modern Society, Brussels (Belgium)

Jan 79

NATO CDSM
OTAN CCMS

COMMITTEE ON THE CHALLENGES
OF MODERN SOCIETY

PB 295003

# Flue Gas Desulfurization Pilot Study Phase I — Survey of Major Installations - Lime/Sludge Flue Gas Desulfurization Process

## Appendix 95-B

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Considering the application of lime/sludge flue gas desulfurization (FGD) systems, the space necessary for the sludge disposal is amongst others an important factor. Therefore the lime/sludge (and the limestone/sludge) technology is economically advantaneous in the U.S.A. due to the availability of inexpensive land, whereas in Europe and in Japan the availability of sufficient space is often prohibitive.

Generally inexpensive lime can be provided to the FGD plants and, as far as available, carbide sludge from chemical industry or alkaline fly ash can be utilized as scrubbing agent. The lime/sludge technology is well developed. Through operation of large scale plants in different countries considerable experience was gathered and reliability of the systems was proven.

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NATO-CCMS STUDY

PHASE I

# Flue Gas Desulfurization Pilot Study Phase I

## Survey of Major Installations - Lime/ Sludge Flue Gas Desulfurization Process

APPENDIX 95-B

Lead Country - Federal Republic of Germany

Prepared by

Dr. N. Haug, Umweltbundesamt, Berlin
G. Oelert, Battelle-Institut e.V., Frankfurt am Main
Dr. G. Weisser, Battelle-Institut e.V., Frankfurt am Main

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## Summary

Considering the application of lime/sludge flue gas desulfurization (FGD) systems, the space necessary for the sludge disposal is amongst others an important factor. Therefore the lime/sludge (and the limestone /sludge) technology is economically advantageous in the U.S.A. due to the availability of inexpensive land, whereas in Europe and in Japan the availability of sufficient space is often prohibitive.

Generally inexpensive lime can be provided to the FGD plants and, as far as available, carbide sludge from chemical industry or alkaline fly ash can be utilized as scrubbing agent. The lime/sludge technology is well developed. Through operation of large scale plants in different countries considerable experience was gathered and reliability of the systems was proven.

Current R+D efforts aim at the following chemical, mechanical and design areas:

- Precipitation of calcium sulfate (gypsum) may cause scaling, which is particularly unwanted in mist eliminators.
- Dissolved salts in the scrubbing agent and chloride built-up in the recycle water can cause corrosion, which is possibly aggravated by the erosive nature of the slurry.
- Pumps, fans and agitators allow mechanical improvements as to their use in this technology.
- Interrelated mechanical and chemical factors may influence the lifetime of expansion joints and piping.
- Finally the optimization of the design parameters like gas flow and slurry distribution, liquid-to-gas ratio, control instrumentation and accessibility for maintenance has to be mentioned.

The advantages and disadvantages of the lime/sludge system are as follows:

Advantages

(1) The basic process is fairly simple and has very few process steps.
(2) Several years of operating experience has led to a greater understanding of the basic principles of this commonly used $SO_2$ control process.
(3) Capital and operating costs are relatively low and reserves of lime are fairly abundant.
(4) $SO_2$ removal efficiencies can be higher than 90 percent.
(5) The two stage treatment of flue gases permits simultaneous removal of $SO_2$ and particulates.
(6) Fly ash does not adversely affect the process in general.

Disadvantages/problems

(1) If not designed carefully and operated attentively, lime systems have a tendency towards chemical scaling, plugging, and erosion. Excess air, pH, fly ash, residence time in the reaction tank, and the presence of $NO_2$ in the flue gas are suspected to be contributing factors.
(2) Fly ash can adversely affect the process by intensification of mechanical wear and erosion in the washing cycle and by increased load of the thickener.
(3) Large quantities of waste must be disposed of in an environmentally acceptable manner.
(4) The sludge has poor settlement properties due to a high sulfite content among others.

Except for one plant, the questionnaires distributed for this study, were returned with inadequate information, so that the evaluation necessarily is incomplete, especially with respect to cost aspects. The individual questionnaire data of all plants has been compiled in table 6 (see appendix) in order to provide an overall survey.

## 1. Background and Introduction

This report is one of a series on the status of Flue Gas Desulfurization Processes in the NATO Countries and Japan. In this program, the United States, the Federal Republic of Germany, and Norway each acted as lead countries to gather information and prepared reports on FGD processes.

The history of lime/limestone scrubbing is closely connected with that of water scrubbing. Dissolved alkaline carbonates ($CaCO_3$ and $MgCO_3$) present in natural water mainly acted as adsorbents for $SO_2$. Moreover, in many of the water-scrubbing tests a small amount of lime or limestone was added.

The most thorough study of water scrubbing appears to have been made by the London Power Co. around 1930.

- Based on experience gained with a test unit (4.5 t/h coal), a large once-through water flow gas washing plant was installed at the Battersea Power Station, London. Initially, the water scrubbing was boosted by addition of limestone slurry; later on, only limestone slurry was applied.

- The Battersea process was later installed also at the London Bankside power plant.

- The London Fulham power station FGD plant was planned next, but for environmental protection reasons no more scrubbing effluent should be discharged into the Thames. In order to produce a solid output of the FGD plant the ICI-Howden process was developed.

- The ICI-Howden Process was first applied on a full scale at the Sir John Power Station in Swansea, England. The FGD unit was shut down due to technical problems.

- The ICI-Howden Process was next applied at the Fulham power station. It operated efficiently until World War II, though maintenance cost was high.

Large-scale lime/limestone scrubbing activities were undertaken subsequently in Russia and Japan:

- 1964: In Russia operation of a $3 \cdot 10^6$ $m^3/h$ waste gas plant attached to an iron ore sintering plant commenced.

- 1966: Start-up of a scrubber on a large sulfuric acid plant in Japan. Today Japan is leading in the number of lime/limestone scrubber installations.

Experimental studies on lime/limestone scrubbing were undertaken in the US by TVA starting in the 1950's. The first major pilot plant (3400 $m^3/h$) was put into operation at a Wisconsin electric power plant in 1965.

Through the efforts of environment protection agencies R+D work on lime/limestone scrubbing has been accelerated in recent years in many industrialized countries.

Many of the $SO_2$ removal processes developed so far use lime instead of limestone to obtain a high removal efficiency economically. The scrubbers used in these wet lime processes are only about half as tall as those used in wet limestone processes.

In Germany Bischoff started up a pilot plant (5000 $m^3/h$) in 1968 at Lünen followed by a semiscale plant (140,000 $m^3/h$) in 1971. At Wilhelmshaven a full scale plant (500,000 $m^3/h$) is operating since February 1977 .

## 2. General Process Description

The priciples of all lime scrubbing systems are essentially the same. When the lime-water slurry or solution comes in contact with flue gas containing $SO_2$, the $SO_2$ is absorbed into the slurry and reacts with the lime to form an insoluble sludge. The by-products include gypsum ($CaSO_4 \cdot 2H_2O$), calcium sulfite hemihydrate ($CaSO_3 \cdot 1/2\ H_2O$), and calcium carbonate ($CaCO_3$). These sludge by-products are generally disposed of in a pond. The processes is schematically shown in Figure 1 (page 2-7).

### 2.1. Process Chemistry

**Chemical Reactions**

$$CaO + H_2O \longrightarrow Ca(OH)_2 \quad (1)$$

$$Ca(OH)_2 + SO_2 \longrightarrow CaSO_3 + H_2O \quad (2)$$

$$CaSO_3 + SO_2 + H_2O \longrightarrow Ca(HSO_3)_2 \quad (3)$$

$$Ca(HSO_3)_2 + Ca(OH)_2 \longrightarrow 2CaSO_3 + 2H_2O \quad (4)$$

Sulfate formation (detrimental), scaling:

$$2CaSO_3 + O_2 \longrightarrow 2CaSO_4 \quad (5)$$

**Control Theory**

Scrubbing liquor is a slurried mixture of calcium hydroxide and calcium sulfite in water. pH of slurry entering the scrubber: 8-10; low pH can cause gypsum scaling; high pH can cause formation of carbonates. Reaction tank (if used): pH = 10 (addition of lime), addition of crystal seed causes homogeneous crystallization. Presence of MgO in the lime allows a subsaturated mode of operation and improves the $SO_2$-removal efficiency.

**Reaction Kinetics**

Reaction with $SO_2$ in the flue gas takes place in the liquid phase; dissolution of calcium sulfite is the rate controlling step for $SO_2$-absorption. In other cases the mass transfer through the interface between gas and liquid is the rate controlling step.

Stoichiometric Requirement 1.0-1,25

## 2.2. Description of Equipment Components

### 2.2.1. Primary Particulate Removal

The venturi scrubber is the first unit in many lime FGD systems. This unit contacts the lime slurry and the flue gas to remove particulates in the flue gas; however, some $SO_2$ removal does occur. If the fly ash can be sold, an electrostatic precipitator (ESP) is preferred for particulate removal because the flue gases will not be cooled and the fly ash results in a dry form. A flue-gas cooler and humidifier must be used in connection with an ESP; it cools the flue gases after passing the ESP, generally to 50 °C. Also, if particulate is removed before the absorber, plugging is reduced in the absorber. Forced-draft fans must be installed in connection with the venturi to provide the necessary turbulent contact of particulates with the slurry within a very short distance.

### 2.2.2. $SO_2$ Absorber

The absorber is the primary $SO_2$ removal unit in the system. Each of the many available designs employs a different method to contact the flue gas with the slurry. The more common unit designs are fixed packing, mobile-bed packing (hollow or solid spheres), sieve or perforated tray, and horizontal or vertical spray towers. Although each unit performs differently, identical parameters have the same general effect on performance.

The scrubber must be constructed of materials that resist corrosion, erosion, and scaling. Most scrubber bodies are fabricated of mild steel lined with an acid-resistant coating such as fiberglass-reinforced polyester (FRP), rubber, or glass flake. Scrubber

internals are made of a variety of materials such as stainless steel, which has a tendency to pit; high nickel alloys, which are expensive; or FRP, which is fragile. No one material seems to stand above the others.

The size and number of modules in a scrubber system are directly related to boiler size, turndown requirements, system availability, and gas-liquid distribution. The boiler system loads fluctuate, and the scrubber system must change to maintain optimum scrubber performance. One method of adjusting to turndown is to shut down the scrubber modules as the load decreases. The more modules in the system, the smoother the transition. Scrubber modules not being used can be scheduled for cleaning and maintenance during periods of low system load, thereby reducing overall scrubber down-time. Having multiple modules also has the advantage of permitting the modules to be smaller. Smaller cross-section areas in the scrubber module promote uniform gas-liquid distribution and improve efficiency.

### 2.2.3. Demister

A demister is necessary to remove entrained water from the scrubber outlet gas so as to prevent downstream equipment from corroding or scaling. Additional energy in the reheater also is required to evaporate the droplets. Two banks of demisters are usually sufficient, but more can be added for additional demisting capability. Demisters also may be subject to scaling and corrosion; therefore soot blowers or spray washers are installed to solve this problem.

Chevron and cyclonic-vane-type demisters are both effective. Although either can be operated in a horizontal or vertical position, demisters operate much more effectively in the vertical position, so the horizontal position is rarely used on new units.

When demisters are operated in the horizontal position, captured water tends to drip back into the gas stream and become reentrained.

### 2.2.4. Reheater

Reheating of stack gas is generally necessary to increase the buoyancy and maintain plume dispersion. This not only helps meet ambient $SO_2$ and $NO_x$ standards at ground level, but also protects downstream equipment and prevents formation of acid mist. Reheating can be accomplished by installing a gas or oil burner that exhausts directly into the stack, installing steam coils to heat the flue gas, injecting preheated air into the stack, or injecting flue gas from the economizer into the stack. In-line heat exchangers are the most popular because of their low initial capital cost, but they tend to corrode and scale. Soot blowers help in many cases, but not always.

### 2.2.5. Slurry Flow

Lime can be received in a milled state. Water is added until the solids content reaches 15 to 25 percent. The slurry is sent to a feed tank, then to the absorber holding tank, where it is mixed with absorber effluent. (If $MgSO_3$ is present, it would be regenerated in the absorber holding tank.) The slurry from the absorber holding tank is pumped, where it reacts through the absorber with $SO_2$ in the flue gas, and then returned to the holding tank. Slurry from the absorber holding tank is pumped to the venturi holding tank. Slurry from this holding tank is pumped to the venturi to scrub out fly ash. The slurry containing the fly ash returns to the venturi holding tank, from which it is pumped to the sludge disposal area for final treatment.

## 2.2.6. Sludge Disposal

Sludge disposal can require 1000 $m^2$ at a small plant and as much as 5,000,000 $m^2$ at a large plant[+], and disposal practices are site specific. A power plant in an arid location might pump the sludge into an unlined pond, allowing the water to evaporate or seep into the ground. In an area where surface run-off or leaching could be a problem, the sludge sometimes is dewatered before being pumped into a lined pond. The water is returned to the system or purged after treatment to reduce chloride ions in the slurry. Plants located in areas where land is relatively expensive, dewater the sludge to about 20 percent liquid level by using clarifiers, thickeners, and vacuum filters, and then fix the sludge by adding a proprietary compound. Fixation is necessary to make the sludge pond a suitable construction site at a later date. A totally closed system where no water is purged into a nearby stream or river has been achieved at the Sherburne County Station, Becker Minnesota. Closed-loop systems are subject to chloride ion concentration buildup in the slurry, especially when coal is used to fire the power plant. Chloride ions accelerate corrosion throughout a closed system, and additional equipment is necessary to remove it.

## 2.2.7. Schematic Flowsheet

A schematic flowsheet common to most of the processes is represented in Figure 1. Table 1 shows the unit operations applied in each individual plant considered in this study. After leaving the boiler combustion chamber, the flue gas (FG) generally passes through an electrostatic precipitator, after which it enters the FGD plant. The FG is treated in a scrubbing system (mostly 2 stages) followed by a demister. To avoid dew point corrosion and to improve the gas flow, a reheater and a fan complete the treatment before the FG enters the stack.

The scrubbing agent, which consists of a low density lime slurry, is handled by the agent preparation and dosing system.

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[+]This is an exceptional case (Bruce Mansfield).

There are different types of wet scrubbers in use at the surveyed plants:

- Fixed throat venturi
- Variable throat venturi
- Turbulent contact absorber (e.g. plastic grid tower)
- Marble bed absorber
- Spray tower
- Perforated plate tower

In the development of wet $SO_2$ scrubbers the following main problems arose:

1) Extreme scaling and clogging of the scrubbers often caused by simultaneous scrubbing of flue dust and $SO_2$
2) Low absorption efficiency in single-stage operation
3) Clogging and wear of spray nozzles
4) Low demister efficiency
5) Scaling and corroding of reheater
6) Scaling, eroding and corroding of fan
7) Tight pH control necessary

Improvement was achieved by:

ad 1 - Electrostatic precipitation of the flue dust upstream the scrubber

ad 2 - Installation of multi-stage scrubbers
ad 3 - Improving of the scrubbing-fluid pH control, nozzle design and choice of nozzle material
ad 4 - Installation of cyclones between scrubber and demister
ad 5 - Direct reheating, e.g. by burners, instead of heat exchangers
ad 6 - Arranging the fan upstream the scrubber, for example
ad 7 - Application of buffer reagents

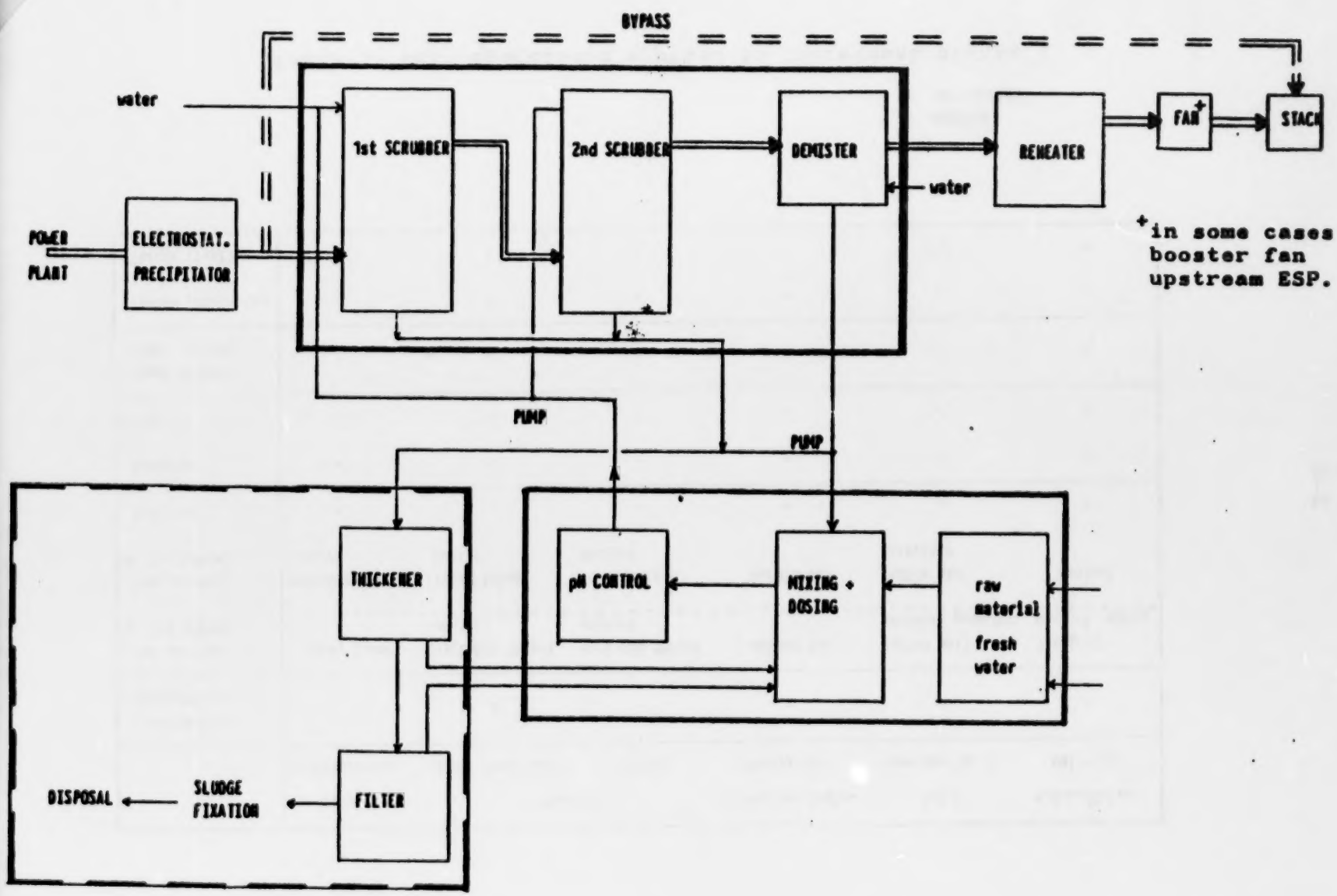


Figure 1: Generalized flow diagram : Lime/sludge processes

| | Bischoff | Chemico | | Combustion Engin. | A.A.F | A.D.L./C.E.A. |
|---|---|---|---|---|---|---|
| | Wilhelmshaven | Bruce Mansfield | Mitsui | Paddys Run | Cane Run No. 4 | Colstrip |
| Electrostatic precipitator | + | o | + | + | + | o |
| 1st scrubber (or 1st stage) | spray tower | variable throat venturi | variable throat venturi | marble bed | wetted wall vertical quencher | integral venturi spray |
| 2nd scrubber (or 2nd stage) | variable throat venturi | fixed throat venturi | fixed throat Venturi | marble bed | mobile bed contacter | venturi |
| Demister | + | + | + | + | + | + |
| Reheater | + | + | + | + | + | + |
| Fan | + | + | + | + | + | + |
| Agent preparation + dosing | + | + | + | + | + | + |
| Sludge dewatering | + | + | + | + | + | + |
| Sludge fixation | o | + | o | + | (+) | o |

+ = applied
o = not applied

Table 1: Unit operations applied in individual plants

## 2.3. Operating Parameters

### 2.3.1. Chemical Parameters

The lime addition rate is 1.0 to 1.25 times stoichiometric requirements. Control of pH to close tolerance is necessary in a lime system; the system must be kept within 0.5 pH of the optimum. This is especially necessary if the boilers have wide variations in load. When the load changes, the appropriate valve must be turned to compensate for the variation or efficiency could be reduced and scaling could occur. The pH is at 10 in fresh slurry, it ranges from 5.5 to 10.0 in the recirculating slurry of the $SO_2$ absorber, and from 8.0 to 10.0 in the first stage or pre-scrubber.

### 2.3.2. Physical Parameters

Liquid-to-gas ratios (L/G's) in the venturi scrubber vary from 0.8 to 15 $l/m^3$ when high particulate removal is desired. Flue gas velocities at the venturi throat vary from 2.5 to 20 m/s and pressure drops across the venturi from 5 to 60 mbar.

L/G's in the $SO_2$ absorber are about 2-8 $l/m^3$. Flue gas velocities in the scrubber are about 5 m/s and pressure drops across the $SO_2$ absorbers vary from 15 to 20 mbar.

Flue gas velocities in a vertical demister average around 6 m/s. The optimum flue gas velocity in horizontal demisters is 2.5 m/s. Although increasing the velocity increases the water removal rate, it also increases the entrainment of water before it can leave the demister. Pressure drops across the demisters vary from 0.3 to 5 mbar.

Reheating of the flue gas to between 22 and 42 $^{o}C$ is required to prevent condensation of the moisture in the gas.

The gross energy necessary to reheat the gas ranges up to 1000 J/kg of flue gas/$^{o}$C of reheat, and is dependent upon the method used.

Absorber hold tank retention times of 5 to 10 m in are required to ensure proper mixing of fresh lime with scrubber effluent. Retention time in the venturi hold tank tends to be slightly longer. Sludge hold tanks, which supply the sludge disposal system, have a retention time of 10 to 20 h.

A typical thickener on a small utility boiler is 20 m in diameter and 5 m high. On a very large utility boiler, it can be 60 m in diameter. The thickener increases the solid content from 10 to 30 percent solids. The same typical small utility boiler would have a thickener overflow of about 100 $m^3/h$, and the large utility boiler an overflow of 800 $m^3/h$.

## 3. Current Status and Plans

Lime/sludge systems are widely used in the United States. Twelve units are in operation in the U.S., Japan and Federal Republic of Germany, five are under construction. The lime/sludge process is viable and is currently on the upswing in countries, where the necessary space is available. However, it is not expected to be the long-term solution, because of rising costs and increasingly stringent waste water and land disposal regulations.

Table 2 shows the summarized status of lime/sludge systems. Table 3 presents important characteristics of each surveyed facility. More detailed information can be found in the survey of questionnaires in Table 6 in the appendix of this report.

| | |
|---|---|
| Total Number of Systems in Operation | 12 |
| Total Number of Systems under Construction | 5 |
| Total Number of Systems Built | 18 |
| Total Number of Systems Surveyed | 7 |
| Year First Placed in Commercial Service | 1972 |
| Number of Utility Systems Using Process | 11 |
| Total MW of these Facilities | 3125 |
| Number of Industrial Combustion Systems | 1 |
| Range of $SO_2$ Removal Efficiencies (%) | 70-92 |
| Range of Fly Ash Removal Efficiencies (%) | 93-100 |
| Range of Availability Factors (%) | 84-100 |

Table 2: Summarized status of lime/sludge systems

| Name of Plants Considered in this Study | Kraftwerk Wilhelmshaven<br>Nordwestdeutsche Kraftwerke AG, Hamburg, Germany | Bruce Mansfield<br>Pennsylvania Power Co. | Mitsui Omuta<br>Mitsui Aluminium Co. |
|---|---|---|---|
| Location | Wilhelmshaven, Germany | Shippingport, Pa., USA | Omuta City, Japan |
| Type of Respective Power Plant | both coal and oil fired / medium load | coal fired | coal fired / base load |
| Size (MW) | 720 | 2,700 | 331 |
| Fuel Characteristics (type/ % S) | coal/ 1.5 heavy oil S/ 2.8 | coal / 4.7 | coal / 2.0-2.4 |
| Heat value (kJ/kg) | 26,500 39,500 | 27,700 | 21,500 |
| Flue Gas Treated ($m^3/h$/ % of total) | 500,000 / 20 - | 2,800,000 / 100 | 510,000 / 100 |
| Year FGD System Started | 2/1977 | 4/1976 | 4/1972 |
| Energy Required (MW) | 10.3 | 25.0 | 3.9 |
| $SO_2$ Removal Efficiency (%) | >80 | 92 | 90 |
| Treatment of Other FG Components (% R.) | particulate: 95 | particulate: 99.8 | particulate: 93.6 |
| Disposition of End Products | pipeline to pond<br>40,000 $m^2$ surface area | pipeline to a ravine<br>5,260,000 $m^2$ area | pipeline to pond |
| Average Availability (%/year) | - | 97 / 1976 | 100 / 1976-77 |

$m^3/h$ = $m^3/h$ under normal conditions (0 °C, 1 bar)

% R. = % Removal

Table 3: Status of surveyed FGD installations (lime/sludge)

| Name of Plants Considered in this Study | Paddys Run Station<br>Louisville Gas and Electric | Cane Run No. 4<br>Louisville Gas and Electric | Colstrip No. 1 + 2<br>Montana Power Co. |
|---|---|---|---|
| Location | Louisville, Ky., USA | Louisville, Ky., USA | Colstrip, Mont., USA |
| Type of Respective Power Plant | coal fired / peaking | coal fired / base load | mine mouth installation / base load |
| Size (MW) | 320 | 178 | 720 |
| Fuel Characteristics (type/ % S) | coal / 3-4 | coal / 3.5-4 | coal / 0.8 |
| Heat value (kJ/kg) | 28,850 | 26,750 | 20.000 |
| Flue Gas Treated ($m^3/h$/ % of total) | 200,000 / 100 | 625,000 / 100 | 2,427,000 / 100 |
| Year FGD System Started | 4/1973 | 8/1976 | 10/1975; 6/1976 |
| Energy Required (MW) | 3.4 | | |
| $SO_2$ Removal Efficiency (%) | 85 | 90 | 70-84 |
| Treatment of Other FG Components (% R.) | particulate: 99 | particulate: 99 | particulate: 99 |
| Disposition of End Products | trucking to landfill area | unlined pond | |
| Average Availability (%/year) | >95 | 83 - 95 | full commercial capacity (84 - 95) |

$m^3/h$ = $m^3/h$ under normal conditions (0 °C/ 1 bar)

% R. = % Removal

Table 3 (continued): Status of surveyed FGD installations (lime/sludge)

## 4. Recent Technological Developments and Solutions to Problem Areas

Great effort has been made to improve the technology and solve the problems associated with the lime scrubber because the low initial investment and operating costs of this system make it a popular choice in the utility industry.

### 4.1. Recent Technological Developments

A significant new development has resulted from the discovery that the presence of Mg ion in the absorber slurry reduces scale, increases $SO_2$ removal rate, and increases gypsum yield. The mechanism postulated is that $MgSO_3$ reduces mass transfer resistances both in the liquid film and at the solid surface interface.

The steps in the reaction begin with the undissociated ion pair $MgSO_3$ and $H_2SO_3$ in the scrubber.

$$H_2SO_3 + MgSO_3 \longrightarrow Mg^{++} + 2HSO_3^- \qquad (6)$$

In the presence of lime the $MgSO_3$ is regenerated in the absorber hold tank by

$$Mg^{++} + 2HSO_3^- + Ca(OH)_2 \longrightarrow MgSO_3 + Ca^{++} + SO_3^{--} + 2H_2O \qquad (7)$$

This supplies calcium ions to feed and results in the final disposal product.

The presence of $MgSO_3$ reduces scaling in the absorber because the regeneration occurs in the absorber hold tank and not in the absorber. The contents of the absorber hold tank are fed to the absorber. The $SO_2$ reacts with the $MgSO_3$ species in solution and forms a soluble product. The slurry returns to the absorber hold tank and is mixed with makeup lime slurry to regenerate the $MgSO_3$ species. The concentration of $CaSO_3 \cdot 1/2H_2O$ and

$CaSO_4 \cdot 2H_2O$ does not build up to the 130 percent to 140 percent supersaturation levels that occur in systems without magnesium and therefore does not precipitate out in the absorber. This reduces the solids content of the slurry in the absorber section.

Gypsum yields are higher because reactions 8 and 9 proceed much faster than reaction 10.

$$MgSO_3 + 1/2\ O_2 \longrightarrow MgSO_4 \quad (8)$$
$$MgSO_4 + CaSO_3 \longrightarrow MgSO_3 + CaSO_4 \quad (9)$$
$$CaSO_3 + 1/2\ O_2 \longrightarrow CaSO_4 \quad (10)$$

The $MgSO_4$ formed readily regenerates in the presence of $Ca(OH)_2$ using the same mechanism shown in equation 7. The magnesium-ion-formed $MgSO_3$ stays in solution for return to the absorber. Gypsum is the more favorable disposal product because its crystalline structure allows closer packing than the calcium sulfite hemihydrate.

## 4.2. Solution to Problem Areas

Three methods recently developed to prevent or reduce scale in the absorber include magnesium sulfite addition, gypsum crystal addition, and unsaturated system operation.

The addition of 3 to 5 percent $MgSO_3$, MgO, $MgCO_3$, or $Mg(OH)_2$ not only reduces scaling but increases the $SO_2$ removal rate and yields more gypsum ($CaSO_4 \cdot 2H_2O$) as opposed to $CaSO_3 \cdot 1/2H_2O$. Gypsum crystals provide suitable crystallization sites where $CaSO_4$ can precipitate in preference to absorber walls and internals. Fresh seed crystals are supplied while the oversized crystals are removed. Unsaturated system operation simply means the $CaSO_3 \cdot 1/2H_2O$ and $CaSO_4 \cdot 2H_2O$ never become superaturated in the scrubber, so they cannot precipitate and cause scaling.

Spray washes and soot blowers have been used to reduce scaling in many places upstream and downstream of the absorber especially to protect reheat coils and demisters.

Excess chloride ion concentrations in the slurry have caused corrosion in downstream equipment (especially reheat coils) and reduced the efficiency of $SO_2$ removal. The chloride ion enters the system through the coal, water, or limestone. Concentrations are found to increase proportionately with the increase in recycled supernatant from disposed sludge. This is the biggest problem facing the application of totally enclosed systems. One solution is to increase the purge rate of the system by increasing the fresh water input.

As a matter of interest, one manufacturer has developed a system in which $CaCl_2$ is added to the slurry to increase $SO_2$ removal; however, special alloys must be used throughout this system to prevent chloride attack.**

The effects of potential problems involving supernatant overflow or leaching into surface water or ground water are not yet known. Anticipated new water pollution regulations will result in totally closed loop scrubbers, which should eliminate any supernatant overflow problems.

**In order to avoid the negative effects of possible pH-values below 7, proprietary water soluble additives are employed. They act as a buffer and react chemically in a manner similar to that of the chlorine present in the closed loop.

## 5. Cost

The questionnaires were returned with inadequate information especially with respect to cost (data from questionnaires are underlined in Table 4); the data in Table 4 are therefore only approximate values, lacking information having been taken from other sources /1, 2, 3, 6/.

Capital costs are partly inflated to the year 1976 using a plant cost index from Chemical Engineering (1957 - 59 = 100; 1972 = 137.2; 1973 = 144.1; 1974 = 165.4; 1975 = 182.4; Jan. 1976 = 187.1.). For evaluating fixed costs per year, a fixed charge factor of 15 % has been assumed for each plant, if no other data have been reported.

Total costs per kWh are subdivided in costs per

- 4000 operating hours p.a.
- 8000 operating hours p.a.

---

1 US $ = 300 Yen
1 US $ = 2.40 DM

| | BISCHOFF | CHEMICO | CHEMICO | COMBUSTION ENGINEERING | AMERICAN AIR FILTER | ARTHUR D. LITTLE/ COMBUSTION EQUIPMENT |
|---|---|---|---|---|---|---|
| | WILHELMSHAVEN (144 MW) | BRUCE MARSFIELD (835 MW) | OHUTA (156 MW) | PADDY'S RUN (65 MW) | CANE RUN (178 MW) | COLSTRIP (720 MW) |
| | Total per kW | Total per kW | Total per kW | Total per kW | Total per kW | Total per kW |
| 1. Reported capital costs ($) year | 8,152,000 /3/ 56,6 1976 | 106,596,000 127,7 /6/ 1976 | 3,440,000 22,1 - 1972 | 3,700,000 56,9 1973 | 10,000,000 56,2 /6/ 1976 | 32,633,000 45,3 1976 |
| Costs inflated to 1976 ($) | | | 4,690,000 30,1 | 4,810,000 74,0 | | |
| 2. Reported annual costs ($) | | | | | | |
| Total fixed costs (fixed charge factor) | 1,223,000 (15 %) | 15,989,000 (15 %) | 817,000 (17.4%) | 555,000 (11,5 %) | 1,500,000 (15 %) | 4,895,000 (15 %) |
| Total variable costs | 1,325,000 /3/ | 10,644,000 /6/ | 1,964,000 | 350,000 | | 1,185,000 |
| 3. Boiler Oper.hrs/ Cap. Factor | exp. 3500/40% | 8000/91% | 7440/85% | 3500/40% | (8000/91%) | 8000/91% |
| Generated MWh, p.a. | 504,000 | 6,680,000 | 1,160,000 | 228,000 | 1,424,000 | 5,760,000 |
| 4. Reported cost per kWh (mills) | | | | | | |
| fixed costs (boiler operation hours) | 2.43 (3500 h) | 4.78 (4000 h) | 1.31 (4000 h) | 2.43 (3500 h) | 2.10 (4000 h) | 1.70 (4000 h) |
| | 1.06 (8000 h) | 2.39 (8000 h) | 0.70 (7440 h) | 1.07 (8000 h) | 1.05 (8000 h) | 0.85 (8000 h) |
| variable costs | 2.63 | 1.59 | 1.69 | 1.54 | (1.80 est.) | 0.206 |
| Total costs per kWh (mills) 4000 h | 5.1 | 6.4 | 3.0 | 4.0 | 3.9 | 2.0 |
| 8000 h | 3.7 | 4.0 | 2.4 | 2.6 | 2.9 | 1.1 |

Table 4: Cost data (data reported in the questionnaires are underlined)

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# 7. Appendix


7.1. Table 5: Conversion Factors 7-2

7.2. Table 6: Questionnaire Data 7-3

7.3. Process Descriptions 7-19

7.3.1. Bischoff Process 7-19

7.3.2. Chemico Process 7-21

7.3.3. Combustion Engineering Process 7-27

7.3.4. American Air Filter Process 7-30

## 7.1. Conversion Factors

| multiply | | by | to obtain |
|---|---|---|---|
| feet | x | 0.30480 | m |
| cub.ft. | x | 28.317 | l |
| Btu/lb | x | 0.55554 | kcal/kg |
| | x | 2.32593 | kJ/kg |
| Btu/h | x | $0.29300 \cdot 10^{-3}$ | kW |
| a.c.f.m. (act. cub.ft. per min.) | x | 1.6992 | $m^3/h$ |
| lb/$10^6$ Btu | x | 1.80005 | mg/kcal |
| | x | 0.42993 | mg/kJ |
| g.p.m. | x | 3.78541 | ltr/min |
| (gal. per min.) | x | 0.22712 | $m^3/h$ |
| gal/1000 $ft^3$ | x | 0.13368 | $ltr/m^3$ |
| $ft^3$/min | x | 1.6992 | $m^3/h$ |
| kcal | x | 4.1868 | kJ (J = Ws) |
| kcal | x | $1.163 \cdot 10^{-3}$ | kWh |
| std. cub. ft per min. | x | 1.60776 | $m^3/h$ (0 °C/1 bar) |
| grains/$ft^3$ | x | 2.288 | $g/m^3$ |
| grains/std. $ft^3$ | x | 2.4182 | $g/m^3$ (0 °C/1 bar) |
| in (inches) water | x | 2.54 | mbar |
| grain | x | 0.0648 | g |
| ton (short) | x | 0.9072 | t |

1 MW corresponds to 2,800 - 3,500 $m^3/h$ flue gas (depending on excess air)

1 std. cub. ft = 28.317 l (60 °F / 14.7 psia)
(15.5 °C/ 1 bar)
= 26.796 l (0 °C/ 1 bar)
= 0.026796 $m^3$

$$\rho_{SO_2} = 2.927 \text{ g/l}$$

Table 5: Conversion factors used in this study

| | BISCHOFF | CHEMICO | CHEMICO | COMBUSTION ENGINEERING | AMERICAN AIR FILTER | ARTHUR D. LITTLE/ COMBUSTION EQUIPMENT |
|---|---|---|---|---|---|---|
| | WILHELMSHAVEN | BRUCE MANSFIELD | OMUTA | PADDY'S RUN | CANE RUN | COLSTRIP |
| **1. GENERAL DESCRIPTION** | | | | | | |
| 1.1 Company | Nordwestdeutsche Kraftwerke AG | Pennsylvania Power Company | Mitsui Aluminium Co. | Louisville Gas and Electric | Louisville Gas and Electric | Montana Power Company |
| 1.2 Plant name | Kraftwerk Wilhelmshaven | Bruce Mansfield Plant | Omuta | Paddy's Run Station | Can Run Power Station | Colstrip Plant |
| 1.3 Preparers name and mailing address | Dr. Wilhelm Bosselmann, Schöne Aussicht 14, 2000 Hamburg 76 phone: 2283 492 | T.W. Day, 11499 Chester Rd., Cincinnati, Ohio 45246 phone: 513-782-4700 | Jumpei Ando, Chuo University, 1-13-27 Kasuga, Bunkyo, Tokyo phone: 03 813 4171 | T.W. Day | T.W. Day | T.W. Day |
| 1.4 Principal plant products | power | power | aluminum | power | power | power |
| Brief description of area surrounding plant site and factors for choice of FGD system | Located on the northeastern coastline of Wilhelmshaven on reclaimed land; surrounded by plain rural land; distance to residential area 3 km. Main advantages: fuel supply from sea; large disposal area available | Located on the Ohio river in the Borough of Shippingport, Pa. A ravine with a 120 m high dam, seven miles from the power plant, acts as waste disposal pond. | Located close to coal mines and other industrial complexes in Omuta, one of the most polluted districts in Japan. | Located on the Ohio river in Rubbertown, about 15 km southwest of the center of Louisville, Ky. The terrain around is relatively flat and highly industrialized. | N/A | N/A |
| 1.5 Plant location | Wilhelmshaven | Shippingport, Pa. | Louisville, Ky. | Louisville, Ky. | Louisville, Ky. | Colstrip, Mont. |
| **1.6 STATION CAPACITY** | | | | | | |
| 1.6.1 Total boiler generating capacity (MW)/number of boilers | 720/1 | 2700/3 | 331/2 | 320/6 | 922/6 | 720/2 |
| 1.6.2 Capacity served by FGD system(MW) | 144 | 835 | 156 | 65 | 178 | 720 |
| amount of flue gas treated ($m^3/h$) | 500,000 | 2,800,000 | 510,000 | 200,000 | 625,000 | 2,427,000 |
| % of boiler flue gas treated by FGD system | 20 | 100 | 100 | 100 | 100 | 100 |
| Number of boilers served | 1 | 1 | 1 | 1 | 1 | 1 |

$m^3/h$ = $m^3/h$ (0 °C, 1 bar)
N/A = not available

| | | BISCHOFF | CHEMICO | CHEMICO | COMBUSTION ENGINEERING | AMERICAN AIR FILTER | ARTHUR D. LITTLE/ COMBUSTION EQUIPMENT |
|---|---|---|---|---|---|---|---|
| | | WILHELMSHAVEN | BRUCE MARSFIELD | OHUTA | PADDY'S RUN | CANE RUN | COLSTRIP |
| 1.7 | TYPE OF FGD SYSTEM | lime/sludge | lime/sludge | lime/sludge | lime/sludge | lime/sludge | lime/sludge |
| 1.8 | Number of scrubber trains in parallel | 1 | 6 | 2 | 2 | 2 | 6 |
| 1.9 | FGD system installed on new or existing boiler | new | new | exist. | exist. | exist. | new |
| 1.10 | STATUS OF FGD SYSTEM operational or under construction, date started | operat. 2/77 | operat. 4/76 | operat. 4/72 | operat. 4/73 | operat. 8/76 | operat. 10/75<br>operat. 6/76 |
| 2. | BOILER DATA | | | | | | |
| 2.1 | Boiler identification number | Wh 1 | No. 1 | No. 1 | No. 6 | No. 4 | No. 1 + 2 |
| 2.2 | Maximum continous heat input (MW) | | 2320 | 464 | 266 | 560 | |
| 2.3 | Max. cont. net generating capacity (MW) | 670 | 835 | 156 | 70 | 190 | |
| 2.4 | flue gas flow rate ($m^3/h$) | 3,736,265 | 5,692,320 | 510,000 | 679,680 | | |
| | temperature at induced draft fan (°C) | 135 | 140.5 | 142 | 168 | | |
| 2.5 | Boiler manufacturer | Deutsche Babcock | | | Foster Wheeler | | |
| 2.5.1 | fuel type | coal or heavy oil | coal | coal | coal | coal | pulverized coal |
| 2.5.2 | firing configuration | double front firing | | front firing | pulverized coal | pulverized coal | tangential |
| 2.6 | Year placed in service | 1976 | | 1971 | 1951 | | 1975 + 1976 |
| 2.7 | Type service | medium load | base load | base load | peaking | base load | base load |
| 2.8 | Stack height (m) | 275 | 290 | 130 | 76 | 91 | 152 |
| 2.8.1 | flue gas exit velocity (m/s) | 28.6 | 8000 | 20 | 27.4 | | 30 |
| 2.9 | Average boiler operation (h/a) | 4000/exp. 1977 | | 7930/72-76 | 3667/1973 | (8000) | 8000/1976 |
| 2.10 | Average boiler capacity factor | 40 %/1977 | | 85 % | 5 %/1974 | | |

| | BISCHOFF | CHEMICO | CHEMICO | COMBUSTION ENGINEERING | AMERICAN AIR FILTER | ARTHUR D. LITTLE/ COMBUSTION EQUIPMENT |
|---|---|---|---|---|---|---|
| | WILHELMSHAVEN | BRUCE MARSFIELD | OMUTA | PADDY'S RUN | CANE RUN | COLSTRIP |
| 2.11 COAL COMPOSITION | | | | | | |
| 2.11.1 Lower heating value (kJ/kg) | 25,100-27,700 | 27,675 | 21,520 | 28,850 | 26,750 | 20,000 |
| (kcal/kg) | 6,000- 6,610 | 6,610 | 5,140 | 6,890 | 6,390 | 4,780 |
| 2.12.2 Sulfur content (%) | ≤ 1.5 | 4.7 | 2.0-2.4 | 3-4 | 3.5-4.0 | 0.8-1.0 |
| 2.11.3 Ash content (%) | 7-15 | 12.5 | 25-29 | 14 | 11-12 | 6.1-12.6 |
| 2.11.4 Chloride content (%) | | | 0.02 | 0.03-0.06 | | 0.01 |
| 2.11.5 Moisture (%) | 6-9 | | 6-8 | 6-12 | | 23.9 |
| 2.12 OIL COMPOSITION | heavy oil S | none | | none | none | none |
| 2.12.1 Grade / heating value (kJ/kg) | 39,360 | | 43,960 | | | |
| (kcal/kg) | 9,400 | | 10,500 | | | |
| 2.12.2 Sulfur content (%) | 2.8 | | 1.0 | | | |
| 2.12.3 Ash content (%) | 0.15 | | 0.01 | | | |
| 2.12.4 Chloride content (%) | | | | | | |
| 2.13 PARTICULATE REMOVAL EQUIPMENT NOT PART OF FGD SYSTEM | | | | | | |
| 2.13.1 Type | electrostatic precipitator | none | elst. precip. | elst. precip. | elst. precip. | none |
| 2.13.2 Manufacturer | Böttner-Schilde-Haas AG | | Toyo Engin. | Research-Cottrell | | |
| 2.13.3 Efficiency, % removal | 99.5 (design) | | 98 | 99.1 | | |
| 2.13.4 Emission rate ($mg/m^3$) | < 75 | | | 114 | | |

| | BISCHOFF | CHEMICO | CHEMICO | COMBUSTION ENGINEERING | AMERICAN AIR FILTER | ARTHUR D. LITTLE/ COMBUSTION EQUIPMENT |
|---|---|---|---|---|---|---|
| | WILHELMSHAVEN | BRUCE MANSFIELD | OHUTA | PADDY'S RUN | CANE RUN | COLSTRIP |
| 3. EMISSION REGULATIONS | | | | | | |
| 3.1 ATMOSPHERIC EMISSIONS | | | | | | |
| 3.1.1 $SO_2$ | 5000 kg/h<br>1981: 2500 kg/h | 1.08 ng/kcal | 256 ppm | 2.16 ng/kcal | 2.16 ng/kcal | 2.16 ng/kcal |
| 3.1.2 Particulate | 187.5 kg/h | 0.04 g/m$^3$ | 150 mg/Nm$^3$ | 0.18 ng/kcal | | 0.18 ng/kcal<br>20 % opacity |
| 3.1.3 NO | | | 540 ppm | none | | 1.26 ng/kcal |
| 3.1.4 Other | flue gas temperature | | | none | | |
| 3.1.5 Legal basis | "Technische Anleitung Luft" and local restrictions | Pa. State Emission Control, Clean Air Act (1970) | local government | Jefferson County, Ky. | federal standard | NSPS |
| 3.2 RESTRICTIONS APPLICABLE TO LIQUID OR SOLID WASTES LEGAL BASIS | disposal pond required | Federal Water Pollution Control Act (1972) | N/A | N/A | N/A | N/A |
| 4. FGD SYSTEM INFORMATION | | | | | | |
| 4.1 Process name | lime/sludge | lime/sludge | lime/sludge | lime/sludge | lime/sludge | lime alkaline fly ash/sludge |
| 4.1.1 Supplier or design company | Bischoff | Chemico | Mitsui Chemico | C.E. | A.A.F. | A.D.L. - C.E.A. |
| 4.1.2 WHY WAS THIS SYSTEM CHOSEN? | Simplest process available 1973 with respect to operating the first demonstration plant in Germany. All other processes considered would have caused higher costs. | Only large scale process out of more than 30 potential systems meeting regulations in late 1970. | Effectiveness of the Chemico scrubber for both $SO_2$ and dust removal expected. | N/A | N/A | Electrostatic precipitator problems with the high resistivity fly ash and the obvious savings in alkali costs by use of fly ash to remove $SO_2$. |
| 4.1.3 PROCESS DESCRIPTION | see text, page 7-19 | see text, page 7-21 | see text, page 7-21 | see text, page 7-27 | see text, page 7-30 | N/A |

| | BISCHOFF | CHEMICO | CHEMICO | COMBUSTION ENGINEERING | AMERICAN AIR FILTER | ARTHUR D. LITTLE/ COMBUSTION EQUIPMENT |
|---|---|---|---|---|---|---|
| | WILHELMSHAVEN | BRUCE MANSFIELD | OHUTA | PADDY'S RUN | CANE RUN | COLSTRIP |
| 4.2 $SO_2$ SCRUBBING AGENT | | | | | | |
| 4.2.1 Name | lime | lime | lime | lime | lime | lime |
| 4.2.2 Chemical composition | (DIN 1060) flocculant | Dravo Corp's thiosorbic lime | carbide sludge | carbide sludge (25 % solids) flocculant (add. rate 4-7 ppm) | carbide lime | alkaline fly ash (14-20 % CaO) |
| Components / % by weight | CaO / > 90 | CaO / MgO / 2-6 | $Ca(OH)_2$ / 90-91 | $Ca(OH)_2$ / 90-92<br>$SiO_2$ / 2.0-2.5<br>$CaCO_3$ / 3-8<br>MgO / 0.1 | $Ca(OH)_2$ / 90-92<br>$SiO_2$ / 2.0-2.5<br>$CaCO_3$ / 3-8<br>MgO 0.1 | CaO |
| 4.2.3 Stoichiometric requirement | 1.25 / design | N/A | 1.05 | 1.0 | 1.0 | 1.0 |
| 4.2.4 Addition rate (kg/h) | 4000 | | | 816 | 2825 | |
| 4.2.5 Particle size (mm) | | | 90 % 200 mesh pass | | | |
| 4.3 REGENERATION AGENT | | | | | | |
| 4.3.1 Name | none | none | none | none | none | none |
| 4.3.2 Composition | | | | | | |
| 4.3.3 Stoichiometric requirement | | | | | | |
| 4.3.4 Addition rate | | | | | | |
| 4.3.5 Particle size | | | | | | |
| 4.4 SALABLE PRODUCT | | | | | | |
| 4.4.1 Name | none | none | none | none | none | none |
| 4.4.2 Chemical composition Components / % by weight | | | | | | |
| 4.4.3 Amount generated/year (t/a) | | | | | | |
| 4.4.4 Sales potential | | | | | | |

| | BISCHOFF | CHEMICO | CHEMICO | COMBUSTION ENGINEERING | AMERICAN AIR FILTER | ARTHUR D. LITTLE/ COMBUSTION EQUIPMENT |
|---|---|---|---|---|---|---|
| | WILHELMSHAVEN | BRUCE MANSFIELD | ONUTA | PADDY'S RUN | CANE RUN | COLSTRIP |
| 4.4.5 BY-PRODUCT RECOVERY PROCESS | none | none | none | none | none | none |
| Name | | | | | | |
| Vendor | | | | | | |
| Process description | | | | | | |
| 4.4a Intermediate product composition | | | | | | |
| 4.5 BY-PRODUCT NUMBER 2 | none | none | none | none | none | none |
| 4.6 WASTE STREAMS | | | | | | |
| 4.6.1 Type of waste | sludge | sludge | calcium slurry | sludge | $CaSO_3 \cdot 1/2\ H_2O$ $CaSO_4 \cdot 2\ H_2O$ | sludge |
| % water | 70-90 | 45-54 | 95 | 55 after vacuum filtration | 80-75 | 40-50 |
| 4.6.2 Amount generated in one hour at full load ($m^3/h$) | 12-35 | | 120 | 9 t/h | 5.465 t/h | 33 t/day, dry basis |
| 4.6.3 Disposal method | pumping into a pond | pumping to a ravine | pumping into a pond | trucking | pumping into a pond | pumped as 30 % slurry |
| 4.6.4 Disposal site and distance from plant (km) | disposal area, 7 m dam 5 | landfill area, 128 m dam 11.3 | 2 | landfill area 1.6 | unlined pond 0.55 | disposal pond 5.5 |
| 4.6.5 Potential effects on environment from sludge disposal | | | one dam side is coated with vinyl sheet to eliminate the environmental problem | | | |
| 4.7 SLUDGE FIXATION PROCESS | none | combined with fly ash slurry and "Calcilox" (Dravo Corp.), stabilized by cementation | none | thickener underflow is stabilized by mixing with lime (50 kg/t dry sludge) | N/A | none |

| | BISCHOFF | CHEMICO | CHEMICO | COMBUSTION ENGINEERING | AMERICAN AIR FILTER | ARTHUR D. LITTLE/ COMBUSTION EQUIPMENT |
|---|---|---|---|---|---|---|
| | WILHELMSHAVEN | BRUCE MARSFIELD | ONUTA | PADDY'S RUN | CARE RUN | COLSTRIP |
| 4.8 FGD EQUIPMENT DATA | | | | | | |
| 4.8.1 FIRST SCRUBBER | | | | | | |
| 4.8.1.1 Type | spray tower + variable throat venturi | variable throat venturi | variable throat venturi + spray | 2 marble bed stages (marble diameter 7.6cm) | wetted wall vertical quencher | integral venturi-spray |
| 4.8.1.2 Liquid(solid)/gas ratio($l/m^3$) | 5-7 | N/A | 10-15 | 2.0-2.4 | 0.8 | 2.0 |
| 4.8.1.3 Gas velocity through absorber or scrubber (m/s) | 4.2-5.8 | N/A | N/A | 2.44-3.66 | 20.3 | 2.74 |
| 4.8.1.4 Absorbent(adsorbent) flow ($m^3/h$) | 2,500 | N/A | N/A | N/A | 400 | 1,400 |
| 4.8.1.5 Gas flow entering scrubber ($m^3/h$) | 500,000 | 2,800,000 | 510,000 | 595,000 x 1/3 | 625,000 | 809,000 x 3 |
| 4.8.1.6 Gas temperature (°C) | 135 | | 136 | 177 | 163 | 149 |
| 4.8.1.7 Gas composition | | | | | | |
| $SO_2$ in → out (ppm) | 1750 → 350 | | 2300 → 220 | | | 650-1000 → 100-300 |
| % removal | 80 | 92 | 90.4 | 85 | 90 | 70-84 |
| Particulate in → out($mg/m^3$) | (<75 → ?) | | 630 → 40 | → 96 | | 7250-16925 → 48 |
| % removal | (design: <75 → <75) | fly ash: 99.8 | 93.6 | 99 | 99 | 99.4 |
| $NO_x$ in → out (ppm) | N/A | N/A | N/A | N/A | N/A | N/A |
| $CO_2$ in → out (ppm) | | | 13.8 → | | | |
| Other in → out | | | | | | |
| 4.8.1.8 Material of construction | C-steel | N/A | SS lined/SUS 316 L | mild steel - stainl. | lined C-steel | C-steel /316 LSS |
| 4.8.1.9 Type of lining | rubber | | resin | flake glass | Precrete G-8 | glass-reinforced polyester |
| 4.8.1.10 Adsorbent and sand losses | | | | | | |
| 4.8.1.11 Number of stages | | | 2 | 2 | | 1 Venturi, 1 spray |
| 4.8.1.12 Packing type and composition | | | | glass marbles 1", glass | | |

| | BISCHOFF | CHEMICO | CHEMICO | COMBUSTION ENGINEERING | AMERICAN AIR FILTER | ARTHUR D. LITTLE/ COMBUSTION EQUIPMENT |
|---|---|---|---|---|---|---|
| | WILHELMSHAVEN | BRUCE MARSFIELD | OHUIA | PADDY'S RUN | CARE RUN | COLSTRIP |
| 4.8.2 SECOND SCRUBBER | | | | | | |
| 4.8.2.1 Type | none | fixed throat | fixed throat venturi | none | mobile bed contactor | venturi |
| 4.8.2.2 Liquid (solid)/gas ratio ($l/m^3$) | | N/A | N/A | | 5.4 | N/A |
| 4.8.2.3 Gas velocity through absorber or scrubber (m/s) | | | | | 4.9 | |
| 4.8.2.4 Absorbent(adsorbent) flow ($m^3/h$) | | | | | 3310 | |
| 4.8.2.5 Gas flow entering scrubber ($m^3/h$) | | | | | 495,175 | |
| 4.8.2.6 Gas temperature ($^oC$) | | | | | 53 | |
| 4.8.2.7 Gas composition | inapplicable | N/A | N/A | inapplicable | | N/A |
| $SO_2$ In → out (ppm) | | | | | 2800* → | |
| % $^2$removal | | | | | 90 | |
| Particulate in → out($mg/m^3$) | | | | | | |
| % removal | | | | | | |
| $NO_x$ In → out (ppm) | | | | | | |
| % removal | | | | | | |
| $CO_2$ | | | | | | |
| Other | | | | | | |
| 4.8.2.8 Material of construction | inapplicable | N/A | N/A | inapplicable | lined C-steel | C.S./316 L S.S. |
| 4.8.2.9 Type of lining | | | | | Precrete G-8 | glass-reinforced polyester |
| 4.8.2.10 Number of stages | | | | | 1 | 1 |
| 4.8.2.11 Packing type and composition | | | | | PVC solid spheres | |

| | BISCHOFF | CHEMICO | CHEMICO | COMBUSTION ENGINEERING | AMERICAN AIR FILTER | ARTHUR D. LITTLE/ COMBUSTION EQUIPMENT |
|---|---|---|---|---|---|---|
| | WILHELMSHAVEN | BRUCE MANSFIELD | CHUTA | PADDY'S RUN | CANE RUN | COLSTRIP |
| 4.8.3 CLEAR WATER TRAY | | | | | none | |
| 4.8.3.1 Type | head nozzles | N/A | N/A | N/A | | valve tray |
| 4.8.3.2 L/G ratio ($l/m^3$) | | | | | | 4-6 |
| 4.8.3.3 Source of water | circulating water | | | | | wash tray pond recycling |
| 4.8.4 DEMISTER | | | | | | |
| 4.8.4.1 Type | axial demister | N/A | Chevron | Chevron | Chevron centrifugal | Chevron |
| 4.8.4.2 Number of passes (stages) | 1 | | 1 | 2 | 2 | 1 |
| 4.8.4.3 Material of construction | C-steel, rubber | | FRP | fibre glass | NORYL | plastic |
| 4.8.4.4 Method of cleaning | | | water spray | water wash-river | spray wash | continous wash |
| 4.8.4.5 Flow rate during cleanings ($m^3/h$) | | | 30 | 23-45 | 9.1 | 16.3 $l/m^2$ |
| 4.8.4.6 Frequency and duration of routine cleaning | | | continous | 8-12 min/8 h | | |
| 4.8.5 REHEATER | | | | | | |
| 4.8.5.1 Type | bare tube heat exchanger | common reheat chamber | after burner with heavy oil | natural gas direct fired | oil direct fired | steam heated exchangers |
| 4.8.5.2 Heat load (kW) | 7300 | 18300 | 406 $kW/m^3$ | 2930 | 3516 | up to 25200 x 2 |
| 4.8.5.3 Heat transfer surface area ($m^2$) | 580 | | | | | 2790 x 2 |
| 4.8.5.4 Temperature of gas in (°C) | 50 | | 52 | 52 | | 49 |
| out (°C) | 90 | | 82 | 74 | | 77-91 |
| 4.8.5.5 Reheater materials of construction | C-steel, resin coated | | refractories | | | Inconel 625 Hastelloy G |

| | | BISCHOFF | CHEMICO | CHEMICO | COMBUSTION ENGINEERING | AMERICAN AIR FILTER | ARTHUR D. LITTLE/ COMBUSTION EQUIPMENT |
|---|---|---|---|---|---|---|---|
| | | WILHELMSHAVEN | BRUCE MARSFIELD | OHATA | PADDY'S RUN | CANE RUN | COLSTRIP |
| 4.8.6 | SCUBBER TRAIN PRESSURE DROP DATA | | | | | | |
| 4.8.6.1 | first scrubber (mbar) | (tests) (20) | N/A | | 28.0-30.5 | 5.1-6.4 | (58) |
| 4.8.6.2 | Second scrubber (mbar) | | | 20 | | 15.2 | |
| 4.8.6.3 | Clear water tray (mbar) | | | | | N/A | |
| 4.8.6.4 | Demister (mbar) | (5) | | 0.3 | 1.3 | 3.8 | |
| 4.8.6.5 | Reheater (mbar) | | | | 0 | | |
| 4.8.6.6 | Ductwork (mbar) | | | | .6.3 | | |
| 4.8.6.7 | Total FGD system (mbar) | | | | 38.0-40.5 | | 75 |
| 4.8.6.8 | I.D. fan $\Delta P$ (mbar) | max. 650 | | booster 31 | 38.0-45.7 | 40.6 | 112 |
| 4.9 | SYSTEM MAKE-UP WATER ADDED ($m^3/h$) | 40.0 + 7.0 | closed loop | 55.0 | 11.36 | 27.44 | 90.85 |
| 4.9.1 | Water added per mole of $SO_2$ removed ($m^3/kg$ mol) | 1.7 + 0.3 (supplementary water) | | 1.2 | .317 | | 1.25 |
| 4.9.2 | Source of make-up water | seawater + drinking water | | industrial water | river | strained river recycled water | river |
| 4.9.3 | Where is water added | scrubber cycle | | scrubber | reaction tank | pump seals, demister wash | demister + pump seals |
| 4.10 | BYPASS SYSTEM | | | | | | |
| 4.10.1 | Can flue gas be pypassed? | yes | N/A | yes | yes | yes | no |
| 4.10.2 | Height of gas discharge when bypassed (m) | 275 | | 130 | 76 | | |
| 4.11 | SLURRY DATA | | | | | | |
| | pH/ solids (% by weight) | | | | | | to disposal pond: 8/30 |
| 4.11.1 | Fresh slurry to scrubber | 7 / ≈ 5 | N/A | 12-13 / 15 | 12.6 / 20-30 | 8.5 / ≈ 10 | - / 10 |
| 4.11.2 | Recirculating slurry | 7 / ≈ 5 | | 7.5-8.3 / 5 | | 5 / ≈ 10 | 5 / 12 |
| 4.11.3 | Waste slurry | 7 / 10-30 | | 7.5 / 4.5- 5 | 8-9.5 / 10 ±.5 | - / ≈ 20 | 5 / 12 |

| | BISCHOFF | CHEMICO | CHEMICO | COMBUSTION ENGINEERING | AMERICAN AIR FILTER | ARTHUR D. LITTLE/ COMBUSTION EQUIPMENT |
|---|---|---|---|---|---|---|
| | WILHELMSHAVEN | BRUCE MARSFIELD | OMUTA | PADDY'S RUN | CARE RUN | COLSTRIP |
| 4.12 SPENT SLURRY SYSTEM | | | | | | |
| 4.12.1 Clarifiers | | | none | | | none |
| 4.12.1.1 Number | 1 | | | 1 | 1 | |
| 4.12.1.2 Diameter (m) | 7 | | | 15.2 | 25.9 | |
| 4.12.2 Solid separation | | | | | | |
| 4.12.2.1 Type | none | thickener 61 m ϕ | | rotary vacuum filter | thickener 22.9 m ϕ | none |
| 4.12.2.2 Cloth area ($m^2$) | | 2920 | | 14 | 412 | |
| 4.12.2.3 Capacity (wet cake) (t/h) | | | | 9 | | |
| 4.13 SPACE REQUIRED, EXCLUSIVE OF SLUDGE DISPOSAL AREA ($m^2$) | 2,000 (400,000) | 5,260,900 | N/A | 40,470 | 567 | 3,000 |
| 4.14 PERSONNEL (man-hours/year) | | N/A | | 6 man crew incl. 3 truck drivers | N/A | |
| 4.14.1 Operating | | | | | | 17,200 |
| 4.14.1.1 Specialists | 10,000 | | 8,040 | | | 108,800 |
| 4.14.1.2 Unskilled | 50,000 | | 16,080 | | | 72,600 |
| 4.14.2 Maintenance and repair | not known | | 15,360 | 2 % of F.C.I. | | |
| 4.15 ENVIRONMENTAL LOAD | | | | | | |
| 4.15.1 Waste water treatment process | none (recycling) | N/A | recover to reuse | none | | none (closed loop) |
| 4.15.2 Concentrations | | | | | | < 20 % opacity |
| 4.15.3 Appearance of flue gas discharge - any mist problems? | none (reheating) | | none | | white steam plume | none |

| | BISCHOFF | CHEMICO | CHEMICO | COMBUSTION ENGINEERING | AMERICAN AIR FILTER | ARTHUR D. LITTLE/ COMBUSTION EQUIPMENT |
|---|---|---|---|---|---|---|
| | WILHELMSHAVEN | BRUCE MARSFIELD | OHUTA | PADDY'S RUN | CANE RUN | COLSTRIP |
| 4.16 FGD SYSTEM OPERATION | | | | | | |
| 4.16.1 % of boiler load FGD can operate | not yet tested | N/A | 50-106 | 100 | 25-100 | 20-120 |
| 4.16.2 Lag time | | | adjusted manually; boiler load normally stays constant | rapidly | as quickly as fans can change speed through fluid drives | follows the boiler |
| 5. ACTUAL COSTS FOR TOTAL FGD INSTALLATION (year) | 2.4 DM = 1 $ | | 300 yen = 1 $ (1972) | (1974) | | |
| 5.1 CAPITAL COSTS ($) | | | | | | |
| 5.1.1 Scrubber | N/A | N/A | 1,403,000 | | N/A | 26,777,000 |
| 5.1.2 Absorbent/regeneration system | | | 1,490,000 | | | - |
| 5.1.3 Sludge disposal system | | | 27,000 | | | 5,916,000 |
| 5.1.4 Site improvements | | | 73,000 | | | - |
| 5.1.5 Land, roads, tracks, substation | | | | | | included |
| 5.1.6 Engineering costs | | | 23,000 | | | |
| 5.1.7 Contractor's fee | | | | | | |
| 5.1.8 Interest during construction | | | 97,000 | | | |
| Construction period (months) | | | 10 | | | |
| 5.1.9 License fees | | | 233,000 | | | |
| 5.1.10 Other | | | 97,000 | | | |
| 5.1.11 Total ($) | 8,152,000 /3/ | 106,596,000 /6/ | 3,440,000 | 3,700,000 | 10,000,000 /6/ | 32,633,000 |
| ($/kW) | 56.6 | 127.66 | 22.05 | 53 | 50 | 45.32 |

| | BISCHOFF | CHEMICO | CHEMICO | COMBUSTION ENGINEERING | AMERICAN AIR FILTER | ARTHUR D. LITTLE/ COMBUSTION EQUIPMENT |
|---|---|---|---|---|---|---|
| | WILHELMSHAVEN | BRUCE MARSFIELD | OHUTA | PADDY'S RUN | CANE RUN | COLSTRIP |
| 5.2 ANNUAL COSTS ($) | | | | | | |
| 5.2.1 Interest | N/A | N/A | 377,000 | | N/A | |
| 5.2.2 Depreciation | | | 440,000 | | | |
| 5.2.3 Insurance and taxes | | | | | | |
| 5.2.4 Total fixed costs | | | 817,000 | 555,000 | | |
| 5.2.5 Labor and overhead<br>Average man hour cost<br>cost/year | | | 97,000 | | | |
| 5.2.6 Raw material breakdown<br>Unit cost<br>Annual cost | | | 463,000 | | | |
| 5.2.7 Utilities, unit cost, annual costs | | | | | | |
| Electricity | | | 667,000 | | | |
| Water | | | 37,000 | | | |
| Steam | | | | | | |
| Fuel | | | 490,000 | | | |
| 5.2.8 Maintenance cost per year | | | 197,000 | | | |
| 5.2.9 Other costs, list | | | 13,000 | | | |
| 5.2.10 Total variable cost per year | 1,325,000 /3/ | 10,644,000 /6/ | 1,964,000 | 350,000 | | 1,185,000 |
| 5.2.11 Total annual cost | | | 2,781,000 | 905,000 | | |
| 5.3 WASTE DISPOSAL COST ($)<br>Unit cost<br>Annual cost | N/A | N/A | N/A | N/A | N/A | N/A |
| 5.4 BY-PRODUCT CREDIT ($) | nil | nil | nil | nil | nil | nil |
| 5.4.1 By-product 1 | | | | | | |
| 5.4.2 By-product 2 | | | | | | |

| | BISCHOFF | CHEMICO | CHEMICO | COMBUSTION ENGINEERING | AMERICAN AIR FILTER | ARTHUR D. LITTLE/ COMBUSTION EQUIPMENT |
|---|---|---|---|---|---|---|
| | WILHELMSHAVEN | BRUCE MARSFIELD | OHUTA | PADDY'S RUN | CANE RUN | COLSTRIP |
| 5.5 NET ANNUAL COST | | | | | | |
| 5.5.1 Cost per kWh for last year (mills) | N/A | 2.7 | 2.5 | 2.5 | N/A | 0.26 |
| 5.5.2 Cost per kWh at maximum continous rating (mills) | | | 2.4 | | | |
| 5.5.3 Cost per kWh without FGD | | | | | | |
| 6. ENERGY REQUIREMENTS | | | | | | |
| Pumps (kW) | 1,100 | | 1,300 | 650 | N/A | N/A |
| Fan (kW) | 1,900 | 6,710 | 2,000 | 780 | | |
| Reheat (kW) | 7,300 | 18,360 | 52 | 1,950 | | |
| Reductant chemicals (kW) | max. 10,000 | | 346 | | | |
| Other (kW) | | | 90 | | | |
| Total (kW) | 10,300 | | 3,867 | 3,380 | | |
| Per t of $SO_2$ removed (kWh/t $SO_2$) | 5,000-10,000 | | 3,000 | 1,707 | | |

| 7. PERFORMANCE HISTORY; OPERATING PROBLEMS AND SOLUTIONS | BISCHOFF | CHEMICO | CHEMICO | COMBUSTION ENGINEERING | AMERICAN AIR FILTER | ARTHUR D. LITTLE/ COMBUSTION EQUIPMENT |
|---|---|---|---|---|---|---|
| | WILHELMSHAVEN | BRUCE MANSFIELD | OMUTA | PADDY'S RUN | CANE RUN | COLSTRIP |
| 7.1 Scrubber system | pH-control instable (due to scaling of pH-probe). Improvement through attenuation. Scrubbing solution distribution had to be adjusted (part of the plastic pipes for instrument and scrubbing-agent lines did not withstand thermal and mechanical stress). Scrubber scaling stable at 5 mm. | No problems stated by Pennsilvania Power Co. | Scaling at the beginning of the operation at the point where fresh lime slurry was fed. Has been eliminated by changing the position of the slurry feeding. | Marble bed support plate repaired. | Mobil: ped contactor plastic spray nozzles deteriorated due to temperature and pressure. Nozzle locations were optimized. | Wet/dry deposits at the scrubber inlet manually removed every 2-3 weeks. New design change promises more than 3 months operation without cleaning. Did not affect boiler operations. Some failures of the protective glass flake linings have been noted due to poor application. Repairs made by applicators. Heat damaged sections repaired. |
| 7.2 Demister | Demister droplet slip could not yet be determined. | | | Scaling; necessary measures not stated. | An anti-spin device was designed and installed within the upper portion of the demister to avoid forming of a standing wave in the systea. Positioning deflectors and drip rings eliminated mist carryover. | A temperature excursion of unit 1 followed blackout and the emergency quench water did not go on because of diesel generator failure and the demister was damaged. Diesel generator for emergency water was repaired. |
| 7.3 Reheater | Scaling of heat exchanger reduces reheat input to off gas. Lower gas temperature causes stack corrosion. Installation of demister slip vaporizer upstream reheater has been proposed. | | Refractory bricks fell down. Repaired. | | | |

| | BISCHOFF | CHEMICO | CHEMICO | COMBUSTION ENGINEERING | AMERICAN AIR FILTER | ARTHUR D. LITTLE/ COMBUSTION EQUIPMENT |
|---|---|---|---|---|---|---|
| | WILHELMSHAVEN | BRUCE MANSFIELD | OHUTA | PADDY'S RUN | CANE RUN | COLSTRIP |
| 7.4 Fan | | | Erosion of impells by fly ash. Occasionally repaired. | | | |
| 7.5 Sludge system | Thickening insufficient, reason is being investigated; tests with alternative separators have been planned. Clay liner of settling pond partially distroyed by waves. | | Erosion of pump. Occasionally repaired. | Clarifier capacity insufficient. Mechanical problems with the slurry pumps. Plugging of strainers and slurry control valves, due to inconsistent slurry particle sizing. | | Excellent settling properties due to 100 % oxidation to sulfate. |
| 7.6 Regeneration system | | | | | | |
| 7.7 By-product system | | | | | | |
| 7.8 Other | Corrosion in silencer and wear in rubber compensators off gas duct. Shut-off valves leaking. | | | Leakage of louvered dampers, not serious. Adjustment. | | |
| 7.9 Availability | Plant operation not stable as yet. | 97 % (7/76 - 12/76) | 100 % (10/76 - 3/77) | > 95 % | 91 % (8/76 - 12/76) | Unit No. 1: 84 % mist eliminator and lining failure caused by heat excursion. Unit No. 2: 95 % |

## 7.3. Process Description

### 7.3.1. Bischoff Process /12/

Residual dust and sulfur are removed from the flue gases (after having passed an ESP) by one and the same scrubbing process. A diluted lime suspension is used as scrubbing solution.

The flue gas is cooled, saturated, and pre-scrubbed in the tuyere area of the scrubber ①. The scrubbing liquid is circulated by pump 2. Fine cleaning takes place in the annular gap scrubber. ② The annular-gap element can be adjusted by a control system. In this way it is possible - even with large fluctuations in gas flow - to produce a high degree of dust and sulfur removal with a constant differential pressure and an invariable scrubbing effect. The droplets entrained with the flue gas are removed by the mist eliminator ③ down to a residue depending on the system and the process. Finally, the clean gas is discharged to the stack. ④

Part of the scrubbing liquid is drawn off by pump 3 and clarified in a thickener ⑤. The clarified liquid is pumped back into the scrubbing system by pump 4.

Water losses are supplemented at the lime-slurry injection stage ⑥ and/or by fresh water addition to the thickener. ⑤⑦

Lime is continuously added to the recirculation loop. An automatically operating mixing installation with a silo is provided for the preparation of lime slurry.

The sludge removed by the thickener consists essentially of calcium sulfite, calcium sulfate, calcium carbonate and washed-out solids. Various possibilities exist for the further use of the sludge after further processing, for example: dumping, use as addition for building materials, or drying, possibly pelletizing, and subsequent dumping.

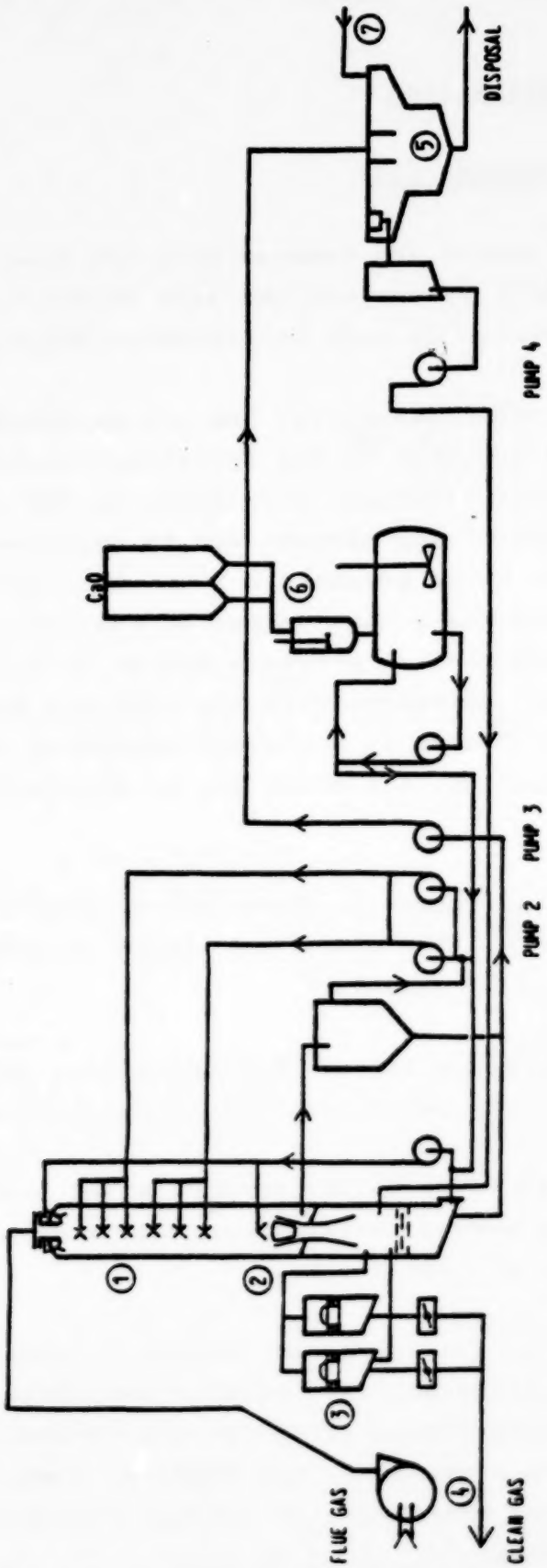



Fig. 2 : FLOW DIAGRAM OF THE BISCHOFF PROCESS /12/

## 7.3.2. Chemico Process /15/

Flue gas leaves the vertical-shaft air heaters ① of the boilers and enters a manifold ② which distributes it to the six separate scrubber inlet ducts. Each duct serves a scrubber train consisting of a scrubber vessel ③, an induced-draft fan ④, and an absorber vessel ⑤. There are six scrubber trains per unit; five are required to handle the flue-gas flow from a single boiler at full load.

The scrubber trains are arranged in two groups of three. Flue gas from the three trains in each group flows together into a reheat chamber ⑥, and is then exhausted up the chimney ⑦. The scrubber and absorber vessels are very similar in certain aspects: size, overall arrangement, and flow in and out. The most important difference is the scrubber's ③ ability to remove nearly all of the flyash from the flue-gas stream by use of an adjustable venturi throat ③; the venturi throat of the absorber is fixed.

Hot flue gas with entrained flyash and sulfur oxides enters each scrubber and accelerates through the venturi section. As the gas reaches its maximum velocity, it impacts upon a curtain of scrubbing liquor. The impact of the accelerating gas on the liquor curtain froms droplets, which provide the surface for dust collection.

The tangential-feed arrangement of the liquor-inlet nozzles and the high pressure drop across the venturi throat substantially influence flyash removal efficiency, as does the amount of scrubbing liquor used per unit of gas flow. To illustrate this: very high liquid-to-gas ratios require the throat to be almost wide open, and the gas velocity relatively low, to achieve a desirable fixed pressure drop. This produces coarse water droplets and thus

a reduction in scrubbing efficiency. Very low liquid-to-gas ratios are likely to starve some of the throat's circumference of water, thus also reducing efficiency.

Flue gas and liquid slurry are separated in the lower section of the scrubber⑧. Here the gas turns 180 degrees upward and flows through the demisters⑨, while the slurry drops to the bottom of the tank, where it is retained for a short time. Slurry level is maintained by automatic adjustment of the discharge flow rate of the scrubber recycle pump. The separated gas passes through the demister section⑨ and then flows to the i-d fan.④ Recycle liquor in the absorber is atomized by the high-velocity gases in the fixed-venturi-throat⑤ section to complete the gas-cleanup process.

Three absorber outlet ducts combine together into a single reheat chamber⑥, where three fuel oil burners reheat the scrubbed flue gas before discharging it up the stack.⑦

Flue gas flow through the scrubbing system is controlled, in conjunction with boiler load, by varying the number of scrubbing trains sharing the total gas flow. The i-d fan inlet dampers are interlocked with their respective i-d fan motors and with the boiler control system. This complex control setup, which consists of numerous permissives, annunciators, and interlocks with the burner management system, allows safe startup of the system and determines which trains will be left operating following a unit trip.

The scrubber recycle bleed to the thickener flows into the thickener distribution⑩ box, a mixing tank with zero-time retention. Here the 7.5 %-solids slurry combines with flyash slurry from the boiler and thickener flocculant and then flows into the thickener. Sludge from the thickener⑪ is pumped to the

adjacent underflow tank. From here, it goes to the waste disposal system(12) or, in case of emergency, to on-site ponds.(13)

Lime-slurry system: When the lime arrives at the plant it is unloaded by a bucket unloader. A conveying system allows the lime to be unloaded directly into either 30-day bulkstorage silos or two 2-day, storage silos(14). The smaller silos are so arranged that the lime can be discharged directly to belt-scale-type feeders(15) and into lime slakers(16), which make the slurry. The slurry is held in a transfer tank(17) for about a half-hour, to help complete the chemical slaking process. It then is pumped to the scrubbing area and collected in a recycle tank(18) located near the absorber vessels. The recycle tank feeds a local recycle loop that has individual branches to each scrubber and absorber vessel. The total lime feed is split between the scrubbers and the absorbers.

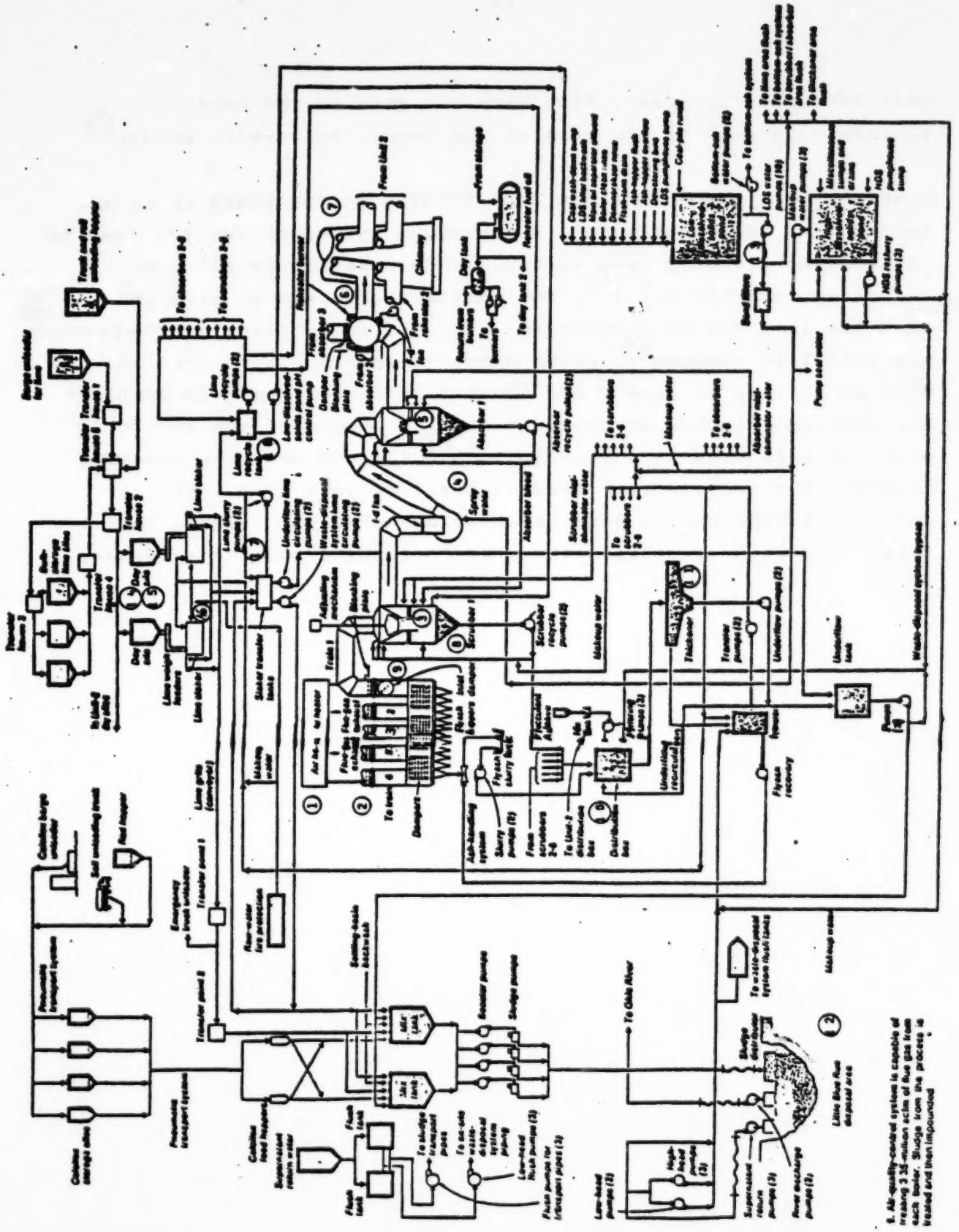
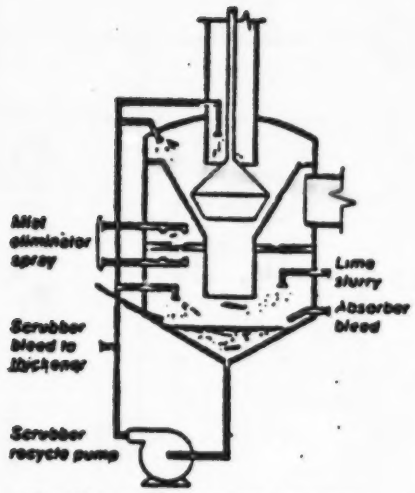
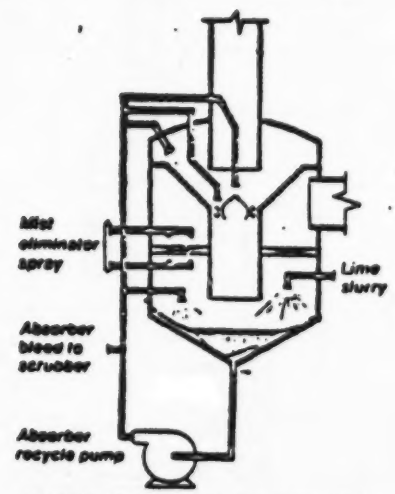


Fig. 3: Flow diagram of the CHEMICO Process /15/

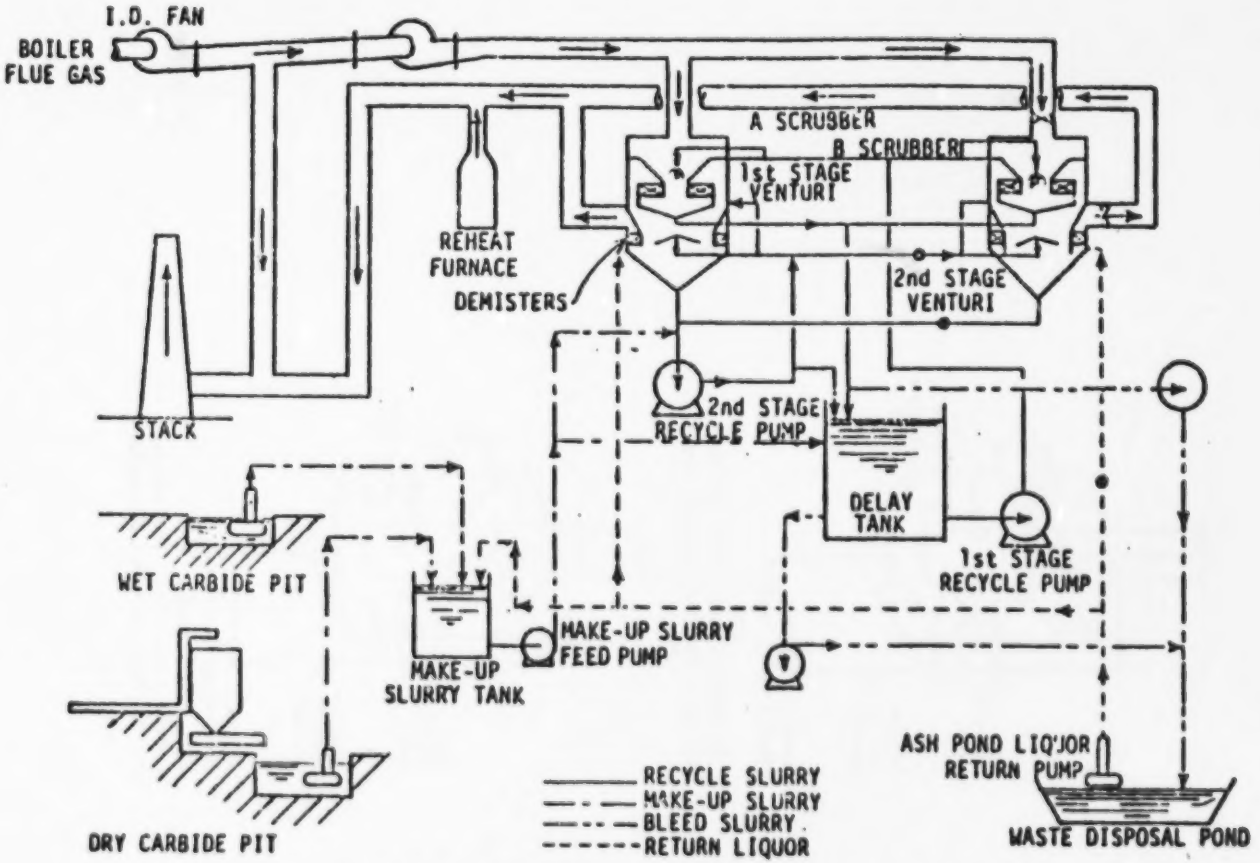



Scrubber removes nearly all of the flyash from the boiler's flue-gas stream




Absorber has a fixed venturi throat; while scrubber's venturi is adjustable

Figure 4: Types of scrubbers in the CHEMICO Process /15/




NOTE: ONLY ONE SCRUBBER SYSTEM PRESENTLY IN OPERATION.

● INDICATES A CLOSED VALVE

⋈ INDICATES A CLOSED DAMPER

Figure 5: Flowsheet of Chemico-Mitsui lime process (Omuta) /5/

### 7.3.3. Combustion Engineering Process /17/

Flue gas enters each scrubber module near the base① and contacts nonatomizing sprays which provide a constant supply of slurry to the underside of the two stages of marble beds.② This slurry of calcium sulfite and calcium hydroxide also serves to cool the flue gas adiabatically to its saturation temperature before it enters the marble bed. The wetted flue gas rises through the bed (consisting of a 3-inch layer of 1-inch-diameter marbles when at rest) and carries the slurry with it. The vigorous action of the marbles mixes the flue gas and slurry to form a "turbulent layer" above the marble bed. The thickness of the layer is controlled by the height of the overflow pots. The turbulent layer provides necessary retention time and mixing intensity to obtain the required degree of $SO_2$ absorption and particulate removal. After emerging from the second marble bed, the clean flue gas passes through a two-stage chevron mist eliminator③ where entrained water droplets are agglomerated and removed. The flue gas then passes through a gas-fired reheater④, through a booster fan⑤, and out the stack.

The underflow from the thickener⑥ is sent to a rotary vacuum filter. Filter cake is trucked to an off-site land-fill area. Vacuum filtrate is recycled to the thickener and pumped back to the reaction tank⑦ to close the liquid effluent loop.

Slurry rejected from below the first bed falls onto a sloping screen in the scrubber bottom. Large particles in the slurry, such as mud or stray marbles, are pulverized and purged periodically from the system to the thickener via a comminutor unit.⑧ Most of the remainder of the reject slurry is returned to the reaction tank⑦ for reuse. All the calcium bisulfite slurry that leaves the beds through the overflow pots is fed by gravity back to the reaction tank, where it is contacted by fresh slaked carbide lime and converted to calcium sulfite.

Other streams entering the reaction tank include weir water from the thickener, return water from the vacuum filter, make-up water, and slurry additives. Mechanical agitators in the tank thoroughly blend the ingredients to maximize the dissolution of additives and to complete calcium salt precipitation reactions. A reaction surge tank[9] downstream from the reaction tank further ensures that if any short circuiting of the reaction tank occurs, precipitation of calcium salts (scale) will occur in the surge tank rather than in the slurry piping. Slurry is pumped back to the scrubber spray nozzles from the reaction surge tank via two half-size slurry pumps. Part of the slurry is bled to the thickener tank to prevent buildup of waste by-product solids in the scrubber.

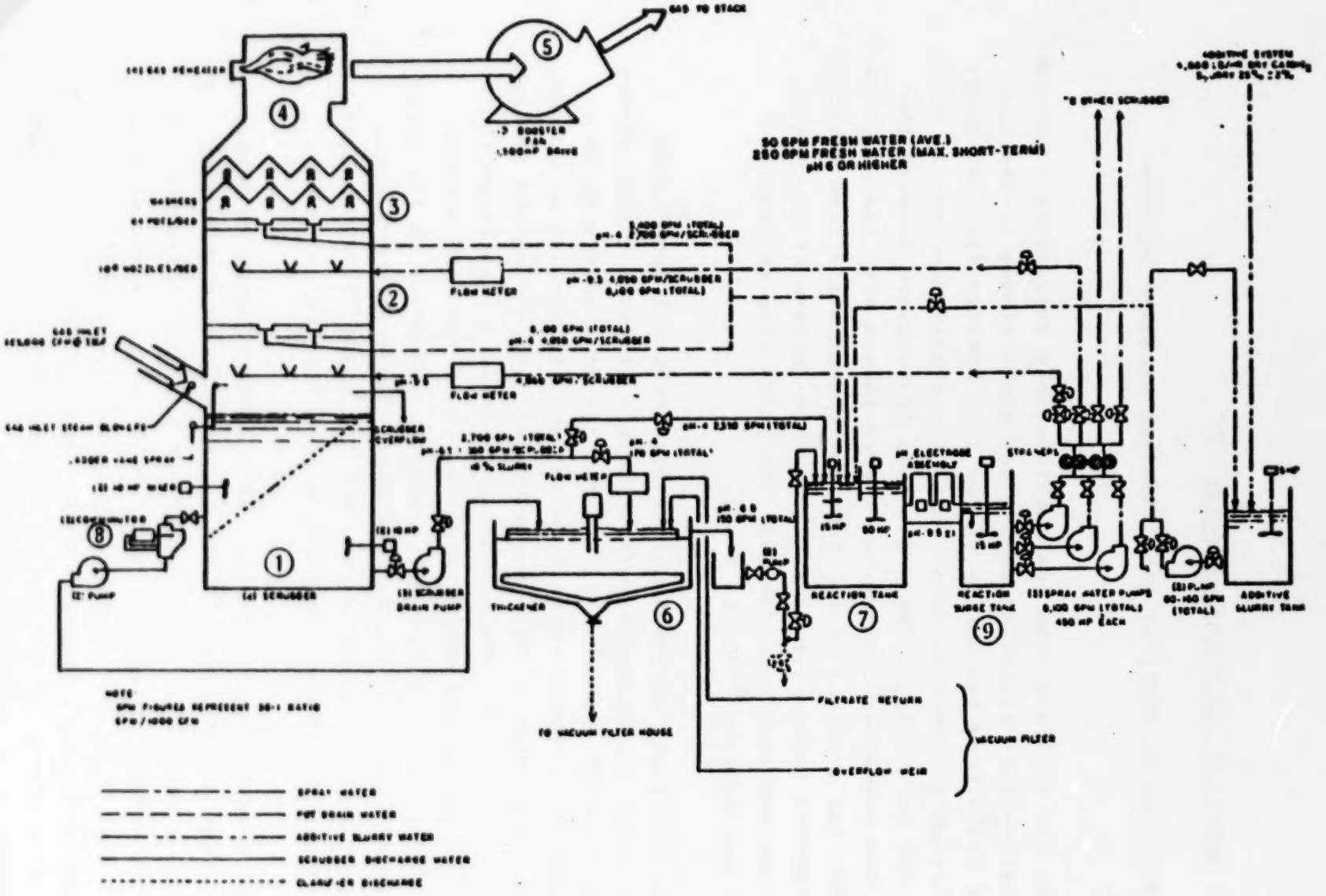



Figure 6: General flow diagram of the FGD system at Paddy's Run. /17/
(Courtesy: Combustion Engineering, Inc.)

## 7.3.4. American Air Filter Process /7/

The FGD system consists of two identical parallel scrubber trains.

The flue gas is drawn from the electrostatic precipitator through a guillotine-type isolation damper and duct① system to the I.D. booster fan②. From the outlet of the I.D. booster fan, the gases flow through a quench section③ which was provided primarily to remove the particulate. The gases then flow upward through the mobile bed contactor④, where the slurry reacts with the $SO_2$. The contactor bed consists of ten separate compartmentalized sections with overhead slurry sprays and below-bed dampers to accommodate gas volume turndown requirements. The gases flow through a centrifugal demister⑧ to the stack.

The slurry/recycle system consists of a reactant tank⑤ with recycle pumps supplying the contactor and venturi, a lime slurry slaking and feed system⑥, and a bleed system discharging to a large pond with return water from the pond to be used as primary make-up. Spent slurry exits the scrubber into the return section of the reactant tank, where make-up water and fresh reagent are added. The second and third compartments of the tank provide for completion of the chemical reaction. Agitators in all three compartments maintain solid suspension. Rubber-lined recycle pumps convey the screened water from the third (feed) compartment back to the venturi scrubber and mobile bed contactor.

The lime slaking system consists of a 500-ton capacity pebble lime storage bin which is filled by pneumatically unloading lime received by rail. The lime storage bin has a vibrating bottom and screw feeder, which feed the pebble lime into an agitated slaking tank. From the slaker, slurry is discharged into a large agitated hold. Reactant pumps feed the reactant as approximately 20 % slurry to the return section of the reactant tank in response to pH sensing instrumentation.

The bleed pumps remove reaction products and collected flyash from the reactant tank to maintain an approximate 10 % slurry within the tanks by pumping slurry to the pond ⑦ where the solids settle, and clear water is returned from the pond by pumps to the return section of the reactant tank ⑤ to maintain the proper liquid level.

Treated water (cleaned river water) for make-up is brought into the system through the pump gland seals, the slaking operation and through the demister wash nozzles.

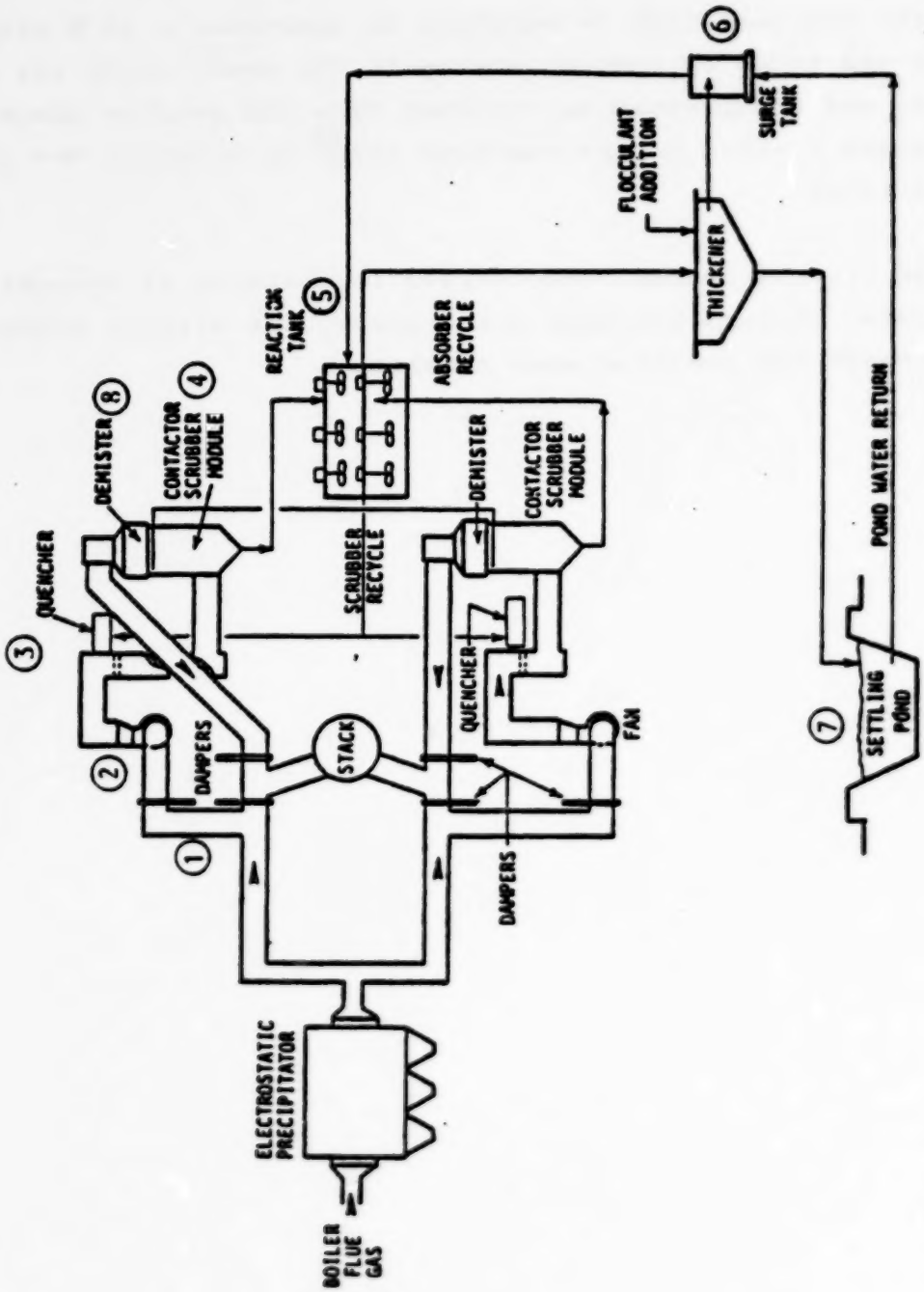



Figure 7: Simplified process flow diagram of the cane run No. 4 FGD System /7/
(American Air Filter Process)